

Spatial Variation of Soil Phosphorus within a Drainage Ditch Network

Robert E. Vaughan, Brian A. Needelman,* Peter J. A. Kleinman, and Arthur L. Allen

ABSTRACT

Agricultural drainage ditches serve as P transport pathways from fields to surface waters. Little is known about the spatial variation of P at the soil-water interface within ditch networks. We quantified the spatial variation of surficial (0–5 cm) soil P within vegetated agricultural ditches on a farm in Princess Anne, MD with an approximately 30-yr history of poultry litter application. Ditch soils from 10 ditches were sampled at 10-m intervals and analyzed for acid ammonium oxalate-extractable P, Fe, Al (P_{ox} , Fe_{ox} , Al_{ox}), and pH. These variables were spatially autocorrelated. Oxalate-P (min = 135 mg kg⁻¹, max = 6919 mg kg⁻¹, mean = 700 mg kg⁻¹) exhibited a high standard deviation across the study area (overall 580 mg kg⁻¹) and within individual ditches (maximum 1383 mg kg⁻¹). Several ditches contained distinct areas of high P_{ox} , which were associated with either point- or nonpoint-P sources. Phosphorus was correlated with Al_{ox} or Fe_{ox} within specific ditches. Across all ditches, Al_{ox} ($r = 0.80$; $p < 0.001$) was better correlated with P_{ox} than was Fe_{ox} ($r = 0.44$; $p < 0.001$). The high level of spatial variation of soil P observed in this ditch network suggests that spatially distributed sampling may be necessary to target best management practices and to model P transport and fate in ditch networks.

THE eutrophication of both fresh and estuarine waters in the USA is a significant ecological and environmental concern. In the year 2002, 408 surface waters in Maryland were identified as impaired with regard to their designated uses (e.g., recreation, fisheries, drinking water), 25% of those were the result of nutrients (USEPA, 2003). Most of these surface waters fall within the Chesapeake Bay watershed. The Chesapeake Bay is the largest estuary in the USA and has experienced the effects of eutrophication for over 30 yr (Boesch et al., 2001). Despite substantial efforts to curb sources of nutrients to the Bay, the ecological, economic, and social impacts of eutrophication are of increasing concern in the Chesapeake Bay Watershed (Boesch et al., 2001).

The southern Delmarva Peninsula has a relatively flat relief and is dominated by poorly drained soils. The water table in this region is close to or at the surface for extended periods of time during the year. To permit cultivation, the region relies on open-air ditches to lower the water table and quickly remove overland flow during periods of intense rainfall. Agricultural ditches

are connected hydrologically to local streams and rivers and are a pathway for sediment and nutrients from agricultural ecosystems (Vadas and Sims, 1998). Ditches are widespread in the USA either as the primary means of land drainage or as collection ditches for tile-drained and irrigated lands (Fausey et al., 1995; Thomas et al., 1995; Evans et al., 1996).

The southern Delmarva Peninsula contains an intense poultry industry, which produced more than 560 million broiler birds and more than 1.3 million Mg of chicken in 2004 (Delmarva Poultry Industry, 2005). Large quantities of poultry litter (poultry manure combined with woodchips, shavings, or other bedding material) are produced each year on the Delmarva Peninsula, much of which is land applied as fertilizer for crops. Poultry litter has a low N/P ratio (Kleinman et al., 2005) such that application of litter at a rate suited to meet crop N requirements generally results in application of P above that required by the crop. The continual application of poultry litter in excess of crop needs leads to the accumulation of P in soils and increased potential for P loss in runoff (Sharpley, 1999).

Ditch soils may act as both a sink and source of P (Sallade and Sims, 1997a, 1997b; Nguyen and Sukias, 2002). Mechanisms that control this relationship include both sedimentation and resuspension of organic matter and P-enriched soil particles, the sorption and desorption reactions of P in solution with mineral and organic compounds, and the uptake and release of P by plants and microorganisms (Johnston et al., 1997).

In acidic soils, such as those found in the Atlantic Coastal Plain, controls of P can be attributed to Fe and Al hydroxides and organic matter cycling (Vadas and Sims, 1998). Low redox potentials develop in ditch soils during periods of warm weather and slow overlying water movement when the decomposition of organic matter is occurring. In the absence of oxygen, ferric Fe may be used as an electron acceptor causing the dissolution of ferric Fe and the subsequent release of Fe-bound P (Reddy et al., 1995; Vadas and Sims, 1998). Aluminum-bound P is not affected by anoxic conditions (Darke and Walbridge, 2000).

Phosphorus in agricultural field soils can exhibit high variation with important implications for agronomic (Gupta et al., 1997) and environmental P management (Larson et al., 1997; Needelman et al., 2001). In wetlands, the distribution of P has been correlated with distance to surface inflows (DeBusk et al., 1994) and sorption capacity (Bruland and Richardson, 2004). The spatial variation of P in ditch soils has not previously been investigated. An understanding of the degree of

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Abbreviations: Al_{ox} , acid ammonium oxalate-extractable Al; DPS, percent degree of P saturation; Fe_{ox} , acid ammonium oxalate-extractable Fe; P_{ox} , acid ammonium oxalate-extractable P; UMES, University of Maryland Eastern Shore.

variation (variance) and spatial patterns (autocorrelation) of P in ditch soils would assist in the understanding of transport and deposition processes (i.e., zones of sink, source, stability), the development of ditch sampling designs, and the improvement of ditch management, modeling, and mass-balance estimation.

The objectives of this study were to (i) assess the spatial variation of oxalate-extractable P, Al, Fe, and pH in a soil depth of 0 to 5 cm within a vegetated agricultural ditch network and (ii) examine the relationships between ditch soil P variation and both ditch soil properties and farm structure.

MATERIALS AND METHODS

Study Area

This study was conducted on a ditch network at the University of Maryland Eastern Shore (UMES) Research Farm (38°12'22" N, 75°40'35" W) located in Princess Anne, Somerset County, MD (Fig. 1). Poultry litter as fertilizer has been applied to many areas of the farm for over 30 yr. Relief on the farm is relatively flat, with most field slopes <5%. The farm has an average elevation of 7 m above mean sea level. Annual precipitation averages 1110 mm, while annual temperature averages 13°C (USDA-NRCS, 2006). The parent materials of field soils at the site are silt loam-textured loess over sandy Atlantic Coastal Plain sediments. Field soils on the farm were mapped primarily as consociations named for the dominant soil series of Othello (Fine-silty, mixed, active, mesic Typic Endoaquults) (Matthews and Hall, 1966). The field soils are generally poorly to very poorly drained and would not be agriculturally productive without artificial drainage.

Agronomic soil fertility tests performed on composite samples from fields surrounding ditches in the study had soil organic matter concentrations that ranged from 17 to 24 g kg⁻¹ with a mean of 21 g kg⁻¹. Field soils were acidic with a pH ranging from 5.3 to 5.8 with a mean of 5.6. The mean Mehlich III-P concentration of the field soils was 511 mg kg⁻¹, ranging from a low of 439 to a high of 583 mg kg⁻¹. Iron extracted by Mehlich III had a range of 294 to 462 mg kg⁻¹ for the field soils with a mean of 401 mg kg⁻¹. Sulfur as SO₄-S ranged from 24 to 35 mg kg⁻¹ in the field soils, with a mean of 35 mg kg⁻¹.

We categorized the ditches within the study area as either primary, shallow collection, or deep collection. Primary ditches are shallow (<1.5 m), drain surface runoff and shallow subsurface flow, often contain stagnant water, and are intermittently inundated. Collection ditches transport outflow from primary ditches. Two types of collection ditches can be discerned: shallow collection (approximately 1.5–2.0 m in depth) and deep collection (>2 m in depth). Shallow-collection ditches are seasonally connected to shallow ground water and intermittently inundated. Deep collection ditches are connected to deep, regional ground water and are permanently inundated. Ditches were labeled using the letter D appended with either an X for primary field ditches or an XX for collection ditches. The letters S and D were used to distinguish between shallow (i.e., S) and deep (i.e., D) collection ditches and a numerical identifier (e.g., 1, 2, 3...) was used to distinguish between ditches of the same type. Thus, DX1 and DX2 distinguish between two primary ditches, whereas DXXS1 and DXXD1 identify shallow and deep collection ditches, respectively.

Ditch Soils

Previous investigations have indicated that soils have formed in the sediments in the ditches at the study area. These sediments are able to support rooted vegetation and horizons have formed through pedogenesis, including organic horizons at the soil surface and gleyed horizons in the profile (Vaughan, 2005). We, therefore, use the term "ditch soils" although the parent material of the soils of these soils is sediment, just as one would discuss a floodplain soil though it is formed from sediment.

Ditch soil profiles were generally A horizons formed in alluvium in-filled since the most recent ditch clean-out over C horizons formed in the original Coastal Plain sediment-derived soils. Many soils had thin Oi horizons overlying the A horizons. Ditch A horizons were dark in color (mean value = 3.3; chroma = 1.8); ditch C horizons were lighter in color (mean value = 5; chroma = 2). Ditch A horizons were loamy in texture while ditch C horizons were coarser in texture and dominated by very gravelly sands, gravelly sands, and sands. Small segments of the ditch network had sandier A horizons. Subangular and granular soil structure was generally observed in the A horizons of primary and shallow collection ditches while the A horizons of deep collection ditches were structureless (high *n*-value). Ditch C horizons were primarily structureless. Redoximorphic features such as depleted matrices and Fe depletions and concentrations were common in both ditch A and C horizons. Ditch soils were generally acidic, with pH ranging from 2.6 to 6.1, and a mean of 4.7. Ditch A horizons were enriched with organic carbon from 0 to 124 mg kg⁻¹ with a mean of 24 mg kg⁻¹. Iron monosulfides (FeS) were observed on the surface of ditches DX1, DX2, and DX3 when they were submerged for extended periods of time. These surficial iron-monosulfides are referred to as monosulfidic black oozes (Smith, 2004). Additionally, geologic sulfidic materials that contain pyrite (FeS₂) were found at a depth below most ditches located on the farm. It is thought

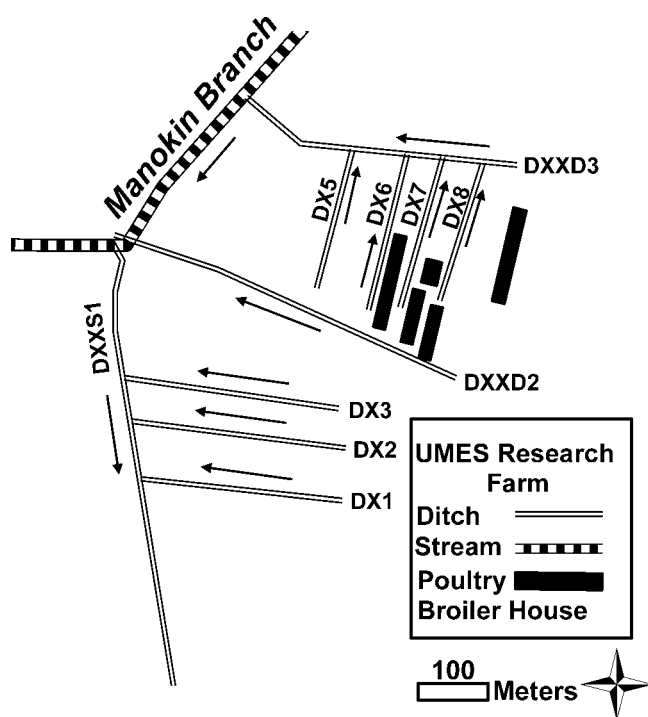


Fig. 1. Overview of the ditch network located at the University of Maryland Eastern Shore Research Farm, Princess Anne, MD. Arrows indicate the direction of water flow within the ditch network (adapted from Vaughan, 2005).

that these sulfidic materials were deposited during a marine transgression, which is believed to have occurred either 82 000 yr B.P. or 125 000 yr B.P. (Toscano and York, 1992; Groot and Jordan, 1999; Wah, 2003).

All ditch soil profiles described were classified to the sub-order level as Aquepts. Endoaquepts accounted for 61% of all profiles, with the subgroups being Sulfic, Aeric, and Hummaqueptic. Particle-size family classes were coarse-loamy or coarse-loamy over sandy or sandy-skeletal.

Field Methods

Soil samples were collected in the spring (March–April) of 2004. At the time of sampling, all ditches contained >8 cm of water. Sampling sites within each ditch were located at 10-m intervals starting from the intersection of a primary ditch and collection ditch using a wheeled measuring device in the field adjacent to each ditch, and then marking the sampling site within the ditch with either a flag or spray paint on the side of the ditch. Samples were composites of three cores (0–5 cm) extracted using a 7.6-cm open-face gouge auger in three evenly spaced (approximately 5 cm) distances perpendicular to the flow direction in the ditch. At every third sampling location (30-m intervals) an additional composite sample was collected within 5 cm of the original sample. The cores were placed into plastic sampling bags and composited by hand. Samples were transported back to the laboratory at air temperature and air-dried within 1 d of sampling. Upon returning to the laboratory and before air-drying, concentrations of what was presumably ferric Fe were observed on the inside of the sealed sample bags. Coarse organic debris was removed and the sample was ground to pass a 2-mm sieve. All analyses were performed on crushed, air-dried samples. A total of 405 samples were collected.

Laboratory Methods

Soil samples were extracted with acid ammonium oxalate elements by shaking 0.5-g air-dried soil with 20 mL 0.1 M $(\text{NH}_4)_2\text{C}_2\text{O}_4 \cdot \text{H}_2\text{O}$ + 0.1 M $\text{H}_2\text{C}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$ (pH adjusted to 3.0) in the dark for 4 h. Extractable Al, Fe, and P (Al_{ox} , Fe_{ox} , P_{ox}) were determined on the supernatant by inductively coupled plasma atomic emission spectroscopy (ICP–AES) (Thermo Jarrel Ash 61 E, Franklin, MA) (Ross and Wang, 1993). Oxalate-extractable P was used rather than the commonly used Mehlich III P as a measure of soil P because of its ability to extract a greater proportion of P that is occluded by or tightly sorbed to Fe oxides that can form in soils with frequent oxidation–reduction cycles. Phosphorus that is occluded by Fe may become soluble under prolonged reducing conditions, therefore making acid ammonium oxalate-extractable P a better measure of P that can be potentially released to overlying drainage waters (Rhue and Harris, 1999). The degree of P saturation (DPS) was estimated as:

$$\text{DPS (\%)} = \left(\frac{\text{P}_{\text{ox}}}{\text{Al}_{\text{ox}} + \text{Fe}_{\text{ox}}} \right) \times 100 \quad [1]$$

where Al_{ox} , Fe_{ox} , and P_{ox} are in mmol kg^{-1} (Breeuwsma and Silva, 1992). We did not apply a coefficient, α , to estimate the proportion of Fe_{ox} and Al_{ox} dedicated to P sorption. The use of α in the literature has been varied (e.g., Lookman et al., 1996; Leinweber et al., 1997; Kleinman and Sharpley, 2002), and a growing number of researchers now do not use an α in calculating DPS.

Samples were analyzed for pH at a soil/water ratio of 1:1. These dry soil pH measurements may be lower than the pH of the soils at their initially moist condition because some ditch samples likely contained oxidizable sulfides (Vaughan, 2005).

Previous investigations in these ditches have revealed the presence of monosulfides at or near the surface of ditch soils at concentrations up to 870 mg kg^{-1} (acid-volatile S) (Vaughan, 2005).

Statistical Analyses

Statistical analyses were performed using S-Plus and S+ Spatial Stats (Insightful Corporation, 2001). Statistical analyses were performed in two parts: (i) all ditches combined and (ii) individual ditches analyzed independently. Kolmogorov–Smirnov tests and descriptive statistics were used to assess normality. Only soil pH was found to be normally distributed; all other variables were found to be normal after log-transformation and were, therefore, log-transformed before statistical analyses (Press et al., 1989). Spatial autocorrelation was described using semivariance analysis (McBratney and Webster, 1986). A pooled variogram was generated for each variable by normalizing semivariance values for each ditch by the variance of that ditch (Goovaerts, 1997, p. 187). This was necessary due to the linear correlation between the mean and the variance (proportional effect). Semivariogram bins, or classes between point pairs, were set at 10-m increments to a maximum of 200 m. A minimum of 103 point pairs were present in all bins.

RESULTS AND DISCUSSION

Ditch Soil Phosphorus Variation

Variograms

Pooled semivariograms indicated that all variables exhibited spatial autocorrelation at the scale of this survey (Fig. 2). Mean nugget semivariance values, calculated

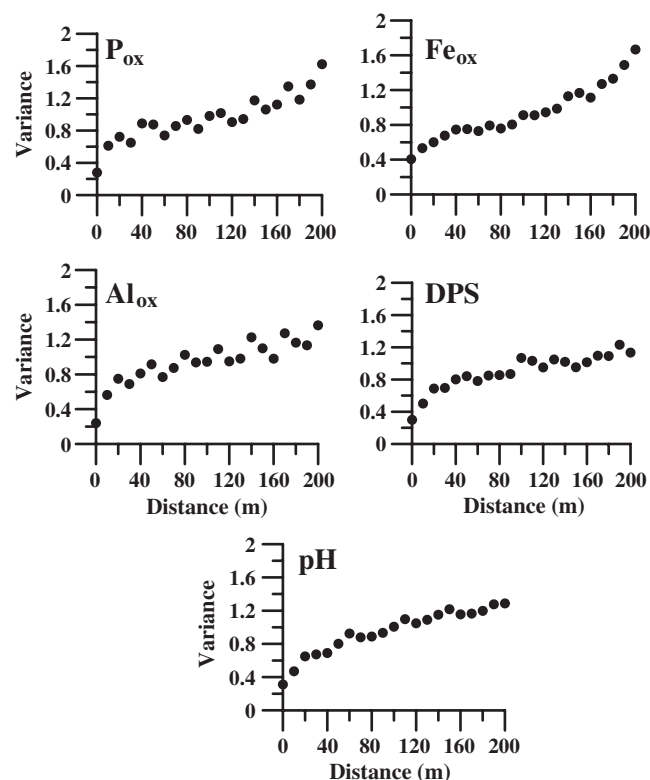


Fig. 2. Pooled semivariograms of ditch soil ammonium oxalate-extractable Fe_{ox} , Al_{ox} , and P_{ox} . Percent degree of P saturation ($\text{DPS} = [\text{P}_{\text{ox}} / (\text{Fe}_{\text{ox}} + \text{Al}_{\text{ox}})] \times 100$) and pH are also presented.

from adjacent samples, were lower than spatially separated mean values for all variables. In particular, P_{ox} and Al_{ox} exhibited high short-range variability. Excluding the nugget values, Fe_{ox} , Al_{ox} , and P_{ox} exhibited a linear increase in semivariance with increasing distance. The semivariance of the 10-m bin in the pH and DPS semivariograms were relatively low while the remaining bins increased linearly with lag spacing. The lack of an observed sill indicates that the range of spatial autocorrelation has not been reached. The semivariograms support the conclusion that the spatial patterns observed in the samples are real trends in the population rather than random noise within the data.

Descriptive Statistics

All ditches were found to be high in P_{ox} , with a mean of 700 mg kg⁻¹, a median of 584 mg kg⁻¹, and a standard deviation of 580 mg kg⁻¹ (Table 1). We do not have P_{ox} data for the field soils at the research site; however, the Mehlich P mean of field soils at the site was 511 mg kg⁻¹. Ditch soils (0–5 cm) studied elsewhere on the Delmarva Peninsula (Delaware's Inland Bays' watershed) had total P (TP) concentrations that ranged from 34 to 1285 mg kg⁻¹ with a mean of 391 mg kg⁻¹ (Sallade and Sims, 1997a). In the current study, ditch soils had oxalate-extractable Fe of 431 to 7503 mg kg⁻¹, with a mean of 2041 mg kg⁻¹, a median of 1739 mg kg⁻¹, and a standard deviation of 1148 mg kg⁻¹ (Table 1). Elsewhere, Bruland and Richardson (2004) reported mean Fe_{ox} values of riparian wetlands in the Coastal Plain of North Carolina from 2770 to 4540 mg kg⁻¹. Sallade and Sims (1997a) reported mean total Fe values of 1290 mg kg⁻¹ in ditch soils. Acid ammonium oxalate-extractable Al_{ox} ranged from 239 to 13 496 mg kg⁻¹, with a mean of 1128 mg kg⁻¹, a median of 929 mg kg⁻¹, and a standard deviation of 1185 mg kg⁻¹ (Table 1). In comparison, mean total Al concentrations of 1815 mg kg⁻¹ were reported by Sallade and Sims (1997a). The DPS of ditch soil samples ranged from 9 to 48%, with a mean of 22%, a median of 21%, and a standard deviation of 7% (Table 2). Soil pH ranged from 3.4 to 6.3, with a mean of 4.9, and a median of 4.9, and a standard deviation of 0.4 (Table 2). The lowest pH values

were found at sites with prominent sulfidic horizons. These pH values are generally lower than those observed in field soils at the site, presumably a result of sulfide oxidation.

Discussion of Areas of Relatively High Phosphorus

There were distinct ditch reaches of higher and lower P_{ox} relative to other reaches in the study area (Fig. 3). To elucidate causes of this variability in P_{ox} , five areas of relatively high P_{ox} were identified and designated as A, B, C, D, and E (Fig. 3, 4, 5, and 6). It appears that areas A and B are higher in P due to local point sources and areas C, D, and E are higher due to increased deposition of P-laden sediment and/or greater P sorption capacity due to a higher Fe_{ox} .

Ditch Areas A and B (Relatively High Acid Ammonium Oxalate-Extractable Phosphorus from Point Sources)

Ditch areas A and B possessed among the highest P_{ox} levels observed in the study area and are examples of hot spots likely arising from point sources of P (Fig. 3). Area A encompasses all of ditch DX8 with a mean P_{ox} of 862 mg kg⁻¹ and relatively little variability across the ditch (C.V. = 35%). The mean Fe_{ox} of ditch DX8 was low in comparison with other ditches (Fig. 4), while oxalate-extractable Al_{ox} values were close to the mean of the entire study area (Fig. 5). A moderate correlation between P_{ox} and Fe_{ox} ($r = 0.65^{**}$) and a strong relationship between P_{ox} and Al_{ox} ($r = 0.84^{***}$) was observed, supporting the inference that Fe and Al are important to P sorption in the acid ditch soils of the study area (Table 3).

Given the high P_{ox} and low Fe_{ox} in area A, the corresponding DPS was very high (Fig. 6), exceeding thresholds of water quality concern proposed elsewhere (Kleinman et al., 1999; Maguire and Sims, 2002; Butler and Coale, 2005). A likely cause of the higher DPS levels in area A is the presence of a poultry litter storage shed 25 m to the west of the head of ditch DX8 (Fig. 1). The shed was used to store poultry manure throughout the year until its application to adjacent fields and other

Table 1. Ammonium oxalate-extractable P, Fe, and Al of ditch soils (0–5 cm) collected from the University of Maryland Eastern Shore Research Farm, Princess Anne, MD.

Parameter	DX1	DX2	DX3	DX5	DX6	DX7	DX8	DXXS1	DXXD2	DXXD3	Total†
P_{ox} ‡											
n	40	41	44	31	33	35	26	46	55	54	405
Min	348	510	225	364	208	269	227	144	135	161	135
Max	1959	1359	1943	1505	811	1790	1635	1192	6919	1329	6919
Mean	794	794	715	651	534	588	862	551	1085	407	700
CV, %	44	22	50	35	24	43	35	46	122	57	83
Std.	353	173	356	227	128	255	298	253	1329	234	580
Fe_{ox} ‡											
Min	1089	1042	662	572	811	744	791	957	472	431	431
Max	7504	4536	7070	6306	2289	2827	1795	5715	4664	7026	7504
Mean	2935	2820	2240	2075	1411	1329	1349	2350	1750	1821	2041
CV, %	50	31	62	55	25	33	23	36	52	74	56
Std.	1457	872	1383	1142	350	432	307	834	905	1346	1148
Al_{ox} ‡											
Min	612	597	560	505	514	381	571	367	239	309	239
Max	1445	2032	13496	2203	1348	1890	2091	1400	13042	1711	13496
Mean	976	1260	1725	805	900	1055	968	768	1678	850	1128
CV, %	20	28	118	46	26	30	31	33	144	42	105
Std.	198	350	2028	366	234	311	296	253	2408	357	1185

† All data combined.

‡ Expressed as a %. Percent degree of P saturation [$DPS = P_{ox}/(Fe_{ox} + Al_{ox})$].

Table 2. Percent degree P saturation (DPS) and moist pH of ditch soils (0–5 cm) collected from the University of Maryland Eastern Shore Research Farm, Princess Anne, MD.

Parameter		DX1	DX2	DX3	DX5	DX6	DX7	DX8	DXXS1	DXXD2	DXXD3	Total†
DPS‡	<i>n</i>	40	41	44	31	33	35	26	46	55	54	405
	Min	16	14	10	15	13	15	16	9	14	11	9
	Max	25	26	26	35	29	42	48	30	42	31	48
	Mean	20	20	19	24	23	24	36	17	27	16	22
	CV, %	10	15	16	17	13	21	19	24	30	25	32
pH	Std.	2	3	3	4	3	5	7	4	8	4	7
	Min	4.2	4.5	4.0	4.4	3.4	4.2	5.0	4.3	3.8	3.8	3.4
	Max	5.0	5.3	6.3	5.6	5.2	5.9	5.7	5.6	5.8	5.6	6.3
	Mean	4.7	4.8	4.7	5.2	4.5	5.1	5.4	4.9	5.2	4.8	4.9
	CV, %	4	4	9	6	11	8	4	6	10	8	8
	Std.	0.2	0.2	0.4	0.3	0.5	0.4	0.2	0.3	0.5	0.4	0.4

† All data combined.
‡ Acid ammonium oxalate-extractable P, Fe, and Al (mg kg^{−1}).

farms during the spring planting season. The shed has a large footprint around it, so that farm equipment can be operated in and around the structure. Due to such traffic, permeability of soils between the shed and ditch DX8 was likely low; thus, it is likely that nutrient-rich runoff from the litter storage shed is directed to area A. While area A was located in a primary ditch, area B comprises roughly 100 m of a deep collection ditch (DXXD2). Area B contained the highest P_{ox} concentration (6919 mg kg^{−1}) found within the study area and ditch DXXD2 had the largest coefficient of variation (CV) of any ditch (123%). The mean P_{ox} of area B was 2617 mg kg^{−1}. Oxalate-extractable Fe was moderate while Al_{ox} was very high relative to other areas (Table 1). The DPS values observed in area B were also quite high, although soils were

not as saturated with P as in area A due to their greater Fe_{ox} and Al_{ox} concentrations (Table 2). As with area A, DPS in area B was likely affected by the presence of an adjacent farm structure, or point source of P, and significant relationships between Fe_{ox} and P_{ox} ($r = 0.66^{***}$) and between Al_{ox} and P_{ox} ($r = 0.98^{***}$) were observed. Near area B, a poultry broiler house (operational until spring of 2004) lay to the north in close proximity (Fig. 1). An access door where poultry litter and broiler chickens were routinely removed was located approximately 15 m to the north of Area B, separated by a compacted gravel road. During heavy rain events, we observed poultry manure solids floating in runoff water that flowed into area B from the direction of the barn. Thus, direct inputs of poultry ma-

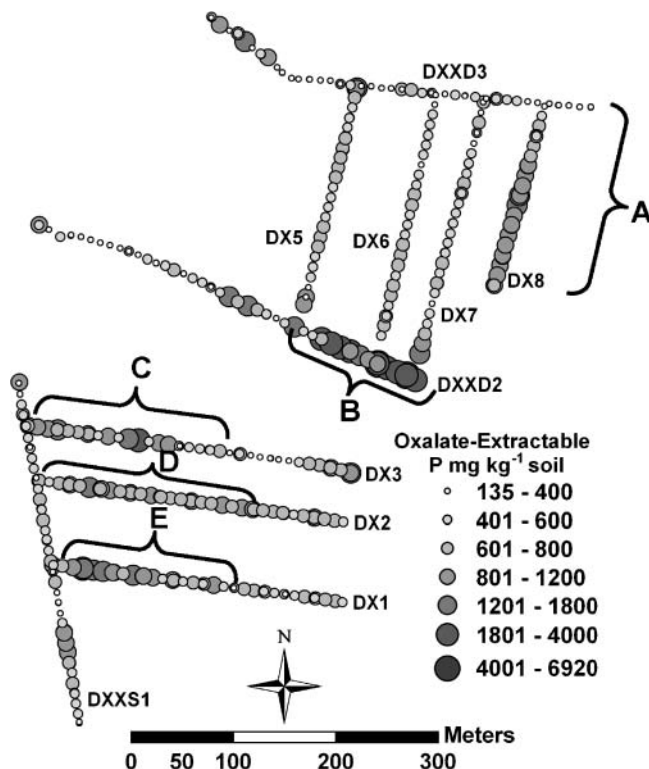


Fig. 3. Ammonium oxalate-extractable P (P_{ox}) concentrations of ditch soils (0–5 cm) at a sampling resolution of 10 m within a ditch network located on the University of Maryland Eastern Shore Research Farm (*n* = 405). Areas identified with the letters A, B, C, D, or E are areas identified as being relatively high in P_{ox}.

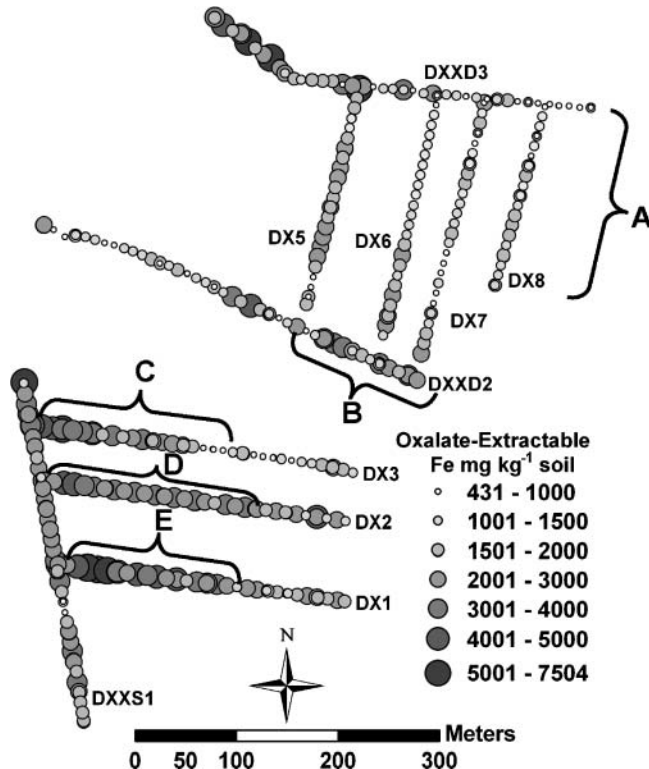


Fig. 4. Ammonium oxalate-extractable Fe (Fe_{ox}) concentrations of ditch soils (0–5 cm) at a sampling resolution of 10 m within a ditch network located on the University of Maryland Eastern Shore Research Farm (*n* = 405). Areas identified with the letters A, B, C, D, or E are areas identified as being relatively high in P_{ox}.

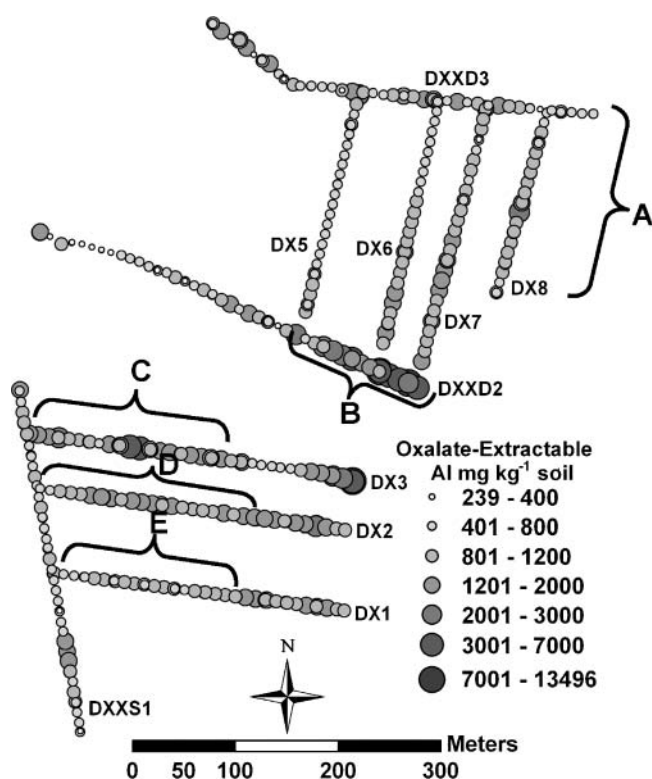


Fig. 5. Ammonium oxalate-extractable Al (Al_{ox}) concentrations of ditch soils (0–5 cm) at a sampling resolution of 10 m within a ditch network located on the University of Maryland Eastern Shore Research Farm ($n = 405$). Areas identified with the letters A, B, C, D, or E are areas identified as being relatively high in P_{ox} .

nure into area B through runoff likely account for the extremely high concentrations of P_{ox} and relatively high DPS measured in area B soils.

For both areas A and B, the transitions from high P_{ox} and DPS to downstream zones of low P_{ox} and DPS are abrupt. In the case of area A, there is an abrupt transition from ditch DX8, a shallow primary ditch, to deep collection ditch DXXD3. We can assume that the flow in DXXD3 is far greater than DX8 because DXXD3 is deeper, has continual baseflow, and receives flow from several ditches. This difference in flow may result in rapid dilution of P transfers from DX8 into DXXD3. In the case of area B, there is a rapid transition within the deep collection ditch DXXD2 from area B (high P_{ox} and Al_{ox}) to an area of relatively low P_{ox} and Al_{ox} (Fig. 3, 4, and 5). Although it is possible that some Al_{ox} found in area B was anthropogenic, it is possible that the change in Al_{ox} values reflects differing alluvial parent materials (i.e., those with contrasting levels of Al_{ox} enrichment or particle size distribution). Indeed, Fe_{ox} also differed substantially between the two areas.

Ditch Areas C, D, and E (Relatively High Acid Ammonium Oxalate-Extractable Phosphorus from Nonpoint Sources)

The relatively high P_{ox} concentrations in ditch soils sampled from ditch areas C, D, and E are likely caused by nonpoint sources of P. Ditch areas C, D, and E are all located at the downstream end of primary ditches that,

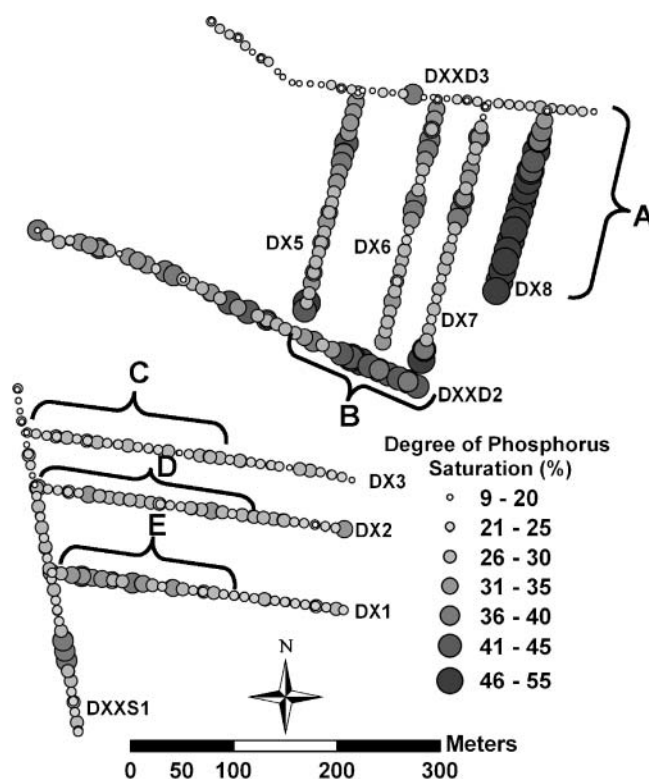


Fig. 6. Percent degree P saturation (DPS) distribution of ditch soils (0–5 cm) at a sampling resolution of 10 m within a drainage ditch network located at the University of Maryland Eastern Shore Research Farm ($n = 405$). Areas identified with the letters A, B, C, D, or E are areas identified as being relatively high in P_{ox} .

superficially, have similar characteristics. Ditch soil samples from ditch areas C, D, and E possessed relatively high P_{ox} and Fe_{ox} concentrations (though substantially lower than areas A and B) but moderate Al_{ox} concentrations and DPS values. The three ditch areas were characterized by pH levels that were considerably lower than other areas in the study area (mean = 4.6) (Fig. 7).

No apparent point sources are located in the proximity of ditches DX1, DX2, or DX3, so nonpoint sources are most likely responsible for the elevated P_{ox} of these areas. All three areas are adjacent to fields to which long-term additions of poultry litter have been made, which is likely the source of the elevated P. However, areas C, D, and E are distinct from the upstream areas of the primary ditches in which they are found. Two non-exclusive hypotheses help to explain areas C, D, and E: sediment deposition and greater P sorption capacity of local parent materials.

All three areas are located at potential depositional areas within the primary ditches, where P may accumulate. Following periods of storm flow, flow in these ditches diminishes rapidly, particularly near their juncture with the collection ditch DXXS1. As the primary ditches broaden, the deposition of sediment is more likely to occur in these areas. Sharpley et al. (1985) described the enrichment of P in eroded sediments relative to the soils from which they were derived, which would explain the higher P_{ox} of areas C, D, and E. Although erosion rates in the region are relatively low

Table 3. Correlation coefficients between ammonium oxalate-extractable P, Fe, and Al; percent degree P saturation (DPS); and moist pH of ditch soils (0–5 cm) by ditch and all ditches combined at the University of Maryland Eastern Shore Research Farm, Princess Anne, MD.

Ditch	pH-Al	pH-Fe	pH-P	pH-DPS	Al-Fe	Al-P	Al-DPS	Fe-P	Fe-DPS	DPS-P
DX1 (n = 40)	–0.04	0.09	0.17	0.25	–0.19	–0.09	–0.39*	0.98***	0.82***	0.86***
DX2 (n = 41)	–0.07	–0.40*	–0.20	0.34*	0.02	0.50**	–0.27	0.68***	–0.18	0.25
DX3 (n = 44)	0.60***	–0.30	0.13	–0.44*	0.00	0.62***	–0.57***	0.59***	0.01	–0.04
DX5 (n = 31)	–0.55**	–0.19	–0.09	0.53*	0.78***	0.78***	–0.37*	0.87***	–0.42*	0.03
DX6 (n = 33)	–0.81***	–0.56**	–0.67***	0.13	0.65***	0.75***	–0.29	0.81***	–0.05	0.33
DX7 (n = 35)	–0.40*	–0.18	–0.15	0.17	0.23	0.48*	–0.11	0.76***	0.46*	0.75***
DX8 (n = 26)	0.14	0.08	0.15	0.21	0.25	0.84***	0.47*	0.65**	0.062**	0.83***
DXXS1 (n = 46)	0.10	0.00	0.15	0.25	0.64***	0.84***	0.45**	0.73***	0.07	0.79***
DXXD2 (n = 55)	–0.40*	–0.31*	–0.36*	0.03	0.56***	0.98***	0.48**	0.66***	0.50***	0.59***
DXXD3 (n = 54)	–0.43**	–0.66***	–0.55***	0.23	0.50***	0.77***	0.17***	0.88***	–0.05	0.31*
Total† (n = 405)	–0.5	–0.30***	–0.07	0.03***	0.18**	0.80***	0.09	0.44***	–0.25	0.44***

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
† All data combined.

and observed ditch flow appeared to be of low turbidity, the increase in P_{ox} of areas C, D, and E is consistent with the deposition of sediments containing higher concentrations of P_{ox} relative to adjacent fields.

Another hypothesis is that the high P_{ox} concentrations in ditch areas C, D, and E result from pedogenic mechanisms. These areas are high in Fe_{ox} relative to other ditch areas (Fig. 4). Phosphorus is most commonly found associated with Fe in acidic Coastal Plain ecosystems; therefore, the high concentration of poorly crystalline Fe (Fe_{ox}) may be acting as a source of binding sites to retain P_{ox} . The cause of such high concentrations of Fe_{ox} in areas C, D, and E may be due to release of ferrous Fe

during the oxidation of Fe monosulfides found at these soil surfaces and of sulfidic materials containing pyrite found at depth in this area of the farm. The oxidation of Fe monosulfides and pyrite can produce significant quantities of Fe in a ferrous (Fe^{2+}) form, which can be converted to a ferric (Fe^{3+}) form on exposure to oxygen (Fanning et al., 2002). This process also releases appreciable amounts of sulfuric acid (Fanning et al., 2002). The production of sulfuric acid through sulfide oxidation could explain the low soil pH values in these ditches (Table 2, Fig. 7).

The additional Fe_{ox} produced by the oxidation of sulfidic materials may have a favorable effect on controlling P losses to ditch DXXS1, which receives water from DX1, DX2, and DX3 (Fig. 1). Ditch DXXS1 is enriched with Fe_{ox} due to underlying sulfidic materials (Fig. 4), but is not enriched with P_{ox} relative to DX1, DX2, and DX3 (Fig. 3). Thus, the enrichment of Fe_{ox} in DX1, DX2, and DX3 at the outlets may be buffering losses of P to DXXS1.

Implications of Phosphorus Variation in Ditch Soils

If the spatial variation of soil P found at the UMES Research Farm is representative of ditches in agroecosystems with a history of manure application and intensive animal agriculture, the findings of this study have important implications for the management and understanding of P fate and transport. Traditionally, ditch management has focused on clean-outs (dredging) and woody vegetation control to maintain hydrologic function. Best management practices are being developed and assessed to maintain and improve hydrologic function while increasing nutrient retention and denitrification (Evans et al., 1996). Ditch management practices are currently applied without sampling or characterization of ditch soils and their geomorphic environment. Knowledge of the spatial variation of P within ditches would allow for targeting of best management practices. For instance, areas within a ditch network identified as having high DPS values could be selectively targeted for clean-outs to reduce P desorption from ditch soils to ditch waters.

If sampling strategies for ditch soils were to be developed, sampling design decisions would include point

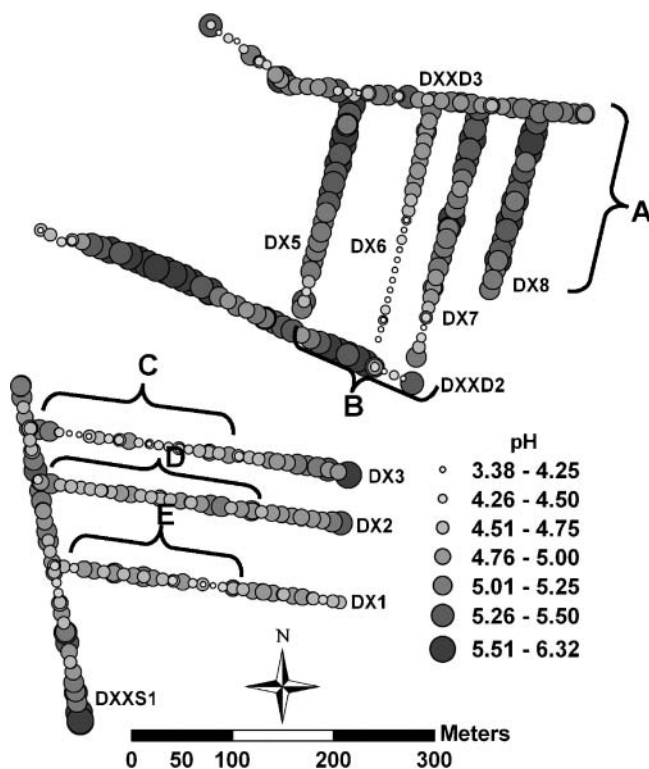


Fig. 7. Moist soil pH (1:1) distribution of ditch soils (0–5 cm) at a sampling resolution of 10 m within a drainage ditch network located on the University of Maryland Eastern Shore Research Farm (n = 405). Areas identified with the letters A, B, C, D, or E are areas identified as being relatively high in P_{ox} .

sampling versus compositing across a ditch, sample number, sampling depth, sampling method, P and other analyses such as Fe and Al, and full-ditch vs. zonal sampling. Sampling strategies and data interpretation developed to understand P loss potential from field soils may not apply to ditches due to redox fluctuations, high organic matter content, and the different hydrology of ditches. Sampling method should allow for the calculation of bulk density to quantify P storage in ditch networks. Measuring soil volume in ditch soils can be difficult due to saturated soils with organic horizons, loamy layers, and sandy layers; the push auger used in the present study caused some densification and therefore we were not able to determine bulk density.

At UMES ditches DXXD2, DX1, and DX3 exhibited substantial within-ditch zonation that would not have been ascertained with composite sampling across a ditch; in each case division of the ditch into thirds would have adequately captured this variation. The zonal nature of the variation of these ditches seems to have been caused by either local farm structure (DXXD2) or geomorphic setting (DX1 and DX3). It may not be necessary to sample ditches in zones that are unaffected by locally variable factors, but this would require methodology to consistently predict which ditches have substantial within-ditch variation.

There are currently no models available to estimate P transport processes within and over ditch soils. To manage and model P losses from ditches, an improved understanding is needed of P transport pathways from the landscape to and through ditch soils, P retention processes in ditch soils, and direct P losses from ditch soils to overlying waters. Areas of very high P and DPS (e.g., areas A and B) may be ditch critical source areas of P to downstream water bodies. Targeting of ditch critical source areas with best management practices may yield large improvements in water quality. Areas of lower P and DPS in the ditch network (e.g., ditch DXXD3) may sorb P from these areas, providing a natural mitigation mechanism. However, if stable and accreting, ditch soils may serve primarily as P sinks over the long term, in which case management should be performed to maximize this role.

SUMMARY AND CONCLUSION

Our results show that ditch surface soils can accumulate very high concentrations of P_{ox} . Within the ditch network, P_{ox} had a high variance (overall standard deviation 580 mg kg^{-1}) and distinct low and high areas. The highest areas of P_{ox} in the ditch network were found near P point sources on the farm. Other relatively high areas of P_{ox} were associated with nonpoint sources and may have been elevated due to greater sediment retention and/or greater Fe_{ox} concentrations, which were related to ferrous Fe released during sulfide oxidation. If the spatial variation of P in these ditches is representative, then spatially distributed sampling may be necessary to target ditch best management practices and to understand and model P transfers and transformations in ditch networks.

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